Indian J. Phys. **68A** (1), 71 – 76 (1994)

IJP A
— an international journal

Phase relationship and absorption coefficient for acoustic wave propagation in *n*-indium antimonide

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Received 16 July 1992, accepted 9 July 1993

Abstract : Recently we have obtained a complex form for the change in distribution function arising due to the passage of acoustic wave through a semiconductor The imaginary part of this function has been used for ascertaining the phase relationship between the self-consistent field and the acoustoelectric current and the real part has been utilised for computing the absorption coefficient for n-indium antimonide.

Keywords : Absorption coefficient, indium antimonide, phase mismatch, acoustoelectric interaction.

PACS No. : 72.50.+b

1. Introduction

The propagation of acoustic wave through a semiconductor has been discussed from many angles. Blotekjaer and Quate [1] have used the coupled mode approach in which one regards the acoustic wave as the lattice mode which are coupled piezo–electrically to the space charge modes of the electron distribution. In the quantum mechanical treatment [2] the drifting carriers are assumed to absorb or emit phonons and the distribution function is calculated from the quantum mechanical equation of motion of the density matrix. The current induced by the acoustic wave is given by the trace of the product of that part of the density matrix which is due to the acoustic wave and the current operator. The current density gives the conductivity tensor from which the absorption coefficient is ascertained. Another approach to the problem is to calculate the conductivity tensor by using the electron distribution function obtained by linearisation of the Boltzmann transport equation [3]. In this semiclassical treatment, the physically important quantities arising due to the electron phonon interaction such as the absorption coefficient, the change in the velocity of sound and the acoustoelectric field are obtained by relating them to the components of the conductivity tensor. In the

phenomenological approach [4], one considers the wave equation, the Poission's equation, the continuity equation, the current density equation and the material equation which on introduction of the plane wave space and time dependence gives a complex form for the elastic stifness C'. The acoustic wave velocity S and the attenuation coefficient α are then obtained by

$$S = \rho^{-1/2} Re\left[(C')^{1/2}\right], \tag{1}$$

$$\alpha = \omega\rho^{1/2} \text{Im}\left[(C')^{-1/2}\right]. \tag{2}$$

An important physical parameter concerning the interaction of acoustic wave with conduction electrons is the phase relationship between the self consistent field $\boldsymbol{E}_1$ and the acoustoelectric current $\boldsymbol{J}_e$. This is so because the acoustic power lost to the electron distribution is proportional to $\boldsymbol{J}_e \cdot \boldsymbol{E}_1$. Out of the approaches discussed above only the phenomenological approach has been reported to yield an expression for this phase relationship. In this approach one expresses $\boldsymbol{J}_e$ in the form

$$\boldsymbol{J}_e = \frac{\sigma \boldsymbol{E}_1}{\gamma + j(\omega/\omega_D)}, \tag{3}$$

which yields the phase ϕ in the form

$$\phi = \tan^{-1}\left(\frac{\omega}{\gamma\omega_D}\right). \tag{4}$$

Recently, Thakur *et al* [5] have obtained a complex form for the change in distribution function arising due to the passage of acoustic wave through a semiconductor. Assuming that the imaginary part of the distribution function corresponds to the different phases of the incoming acoustic wave and the resulting interaction, the phase relationship between the self consistent field $\boldsymbol{E}_1$ and the acoustoelectric current $\boldsymbol{J}_e$ has been ascertained. The real part of the distribution function has been utilised to compute the absorption coefficient for n-indium antimonide.

2. The distribution function

When an acoustic wave propagates through a semiconductor, it perturbs the distribution function of the carrier electrons. Assuming that the perturbation is small, one can make use of the transport equation for obtaining an expression for the change in distribution function corresponding to the acoustic wave interaction with the carrier electrons. The dominant scattering processes are elastic and the scattering time does not depend on electric and magnetic fields. So one can make use of the relaxation time approximation for linearising the transport equation. Further, the acoustic wave is periodic in space and time. So the change in

distribution function must also be a similar function of space and time. These assumptions have enabled Thakur *et al* [5] to express the change in distribution function in the form

$$f_1 = \left(\frac{\nu}{\nu^2+\omega^2}\right)\left[v_k \frac{\partial f_0}{\partial \varepsilon}\left(e\boldsymbol{E}_{\text{eff}} + \frac{\varepsilon(k)-\zeta}{T}\cdot \nabla T\right)\right.$$

$$\left. + v_k \frac{\partial f_1}{\partial \varepsilon}\left(e\left(\boldsymbol{E}_0 - \frac{1}{e}\nabla\zeta\right) + \frac{3}{2}k_0\nabla T\right) + \frac{n_1}{\zeta}\cdot\frac{f_0}{n_0}\right]$$

$$-\left(\frac{i\omega}{\nu^2+\omega^2}\right)\left[v_k \frac{\partial f_0}{\partial \varepsilon}\left(e\boldsymbol{E}_{\text{eff}} + \frac{\varepsilon(k)-\zeta}{T}\nabla T\right)\right.$$

$$\left. + v_k \frac{\partial f_1}{\partial \varepsilon}\left(e\left(\boldsymbol{E}_0 - \frac{1}{e}\nabla\zeta\right) + \frac{3}{2}k_0\nabla T\right) + \frac{n_1 f_0}{\tau\, n_0}\right], \tag{5}$$

where $\nu\left(=\frac{1}{\gamma}\right)$ is the collision frequency, ω is the frequency of the incoming acoustic wave, f_0 is the equilibrium distribution function, n_0 is the carrier concentration in the absence of the acoustic wave and the external fields, n_1 is the change in carrier concentration induced by the propagating acoustic wave, k_0 is the Boltzmann constant, ∇T is the temperature gradient, ρ is the density of the material used, $\varepsilon(k)$ is the energy of the carrier in state k, $\boldsymbol{E}_0$ is the external d.c. field, T is the temperature of the semiconductor, $\boldsymbol{E}_{\text{eff}}$ is the effective electric field, e is the electronic charge and v_k is the velocity of the carrier in state k.

In the absence of temperature gradient, ∇T will be zero. Further, under the assumption of small perturbation, the term $v_k \cdot \frac{\partial f_1}{\partial \varepsilon}$ will be negligibly small. Under such a situation, the change in distribution function will be given by

$$f_1 = \left(\frac{\nu}{\nu^2+\omega^2}\right)\left[v_k \frac{\partial f_0}{\partial \varepsilon} e\boldsymbol{E}_{\text{eff}} + \frac{n_1}{\tau}\frac{f_0}{n_0}\right]$$

$$-i\left(\frac{\omega}{\nu^2+\omega^2}\right)\left[v_k \frac{\partial f_0}{\partial \varepsilon} e\boldsymbol{E}_{\text{eff}} + \frac{n_1}{\tau}\frac{f_0}{n_0}\right]. \tag{6}$$

The imaginary part of this equation corresponds to the different phases of the incoming acoustic wave and the resulting interaction whereas the real part contributes to the current density.

3. Phase relationship

The phase angle ϕ between the acoustoelectric current J_e and the acoustoelectric field $\boldsymbol{E}_1$ is the ratio of the imaginary and the real part of the distribution function. Equation (6), therefore, yields

$$\phi = \tan^{-1}\left(\frac{-\omega}{\nu}\right) \tag{7}$$

For $\nu >> \omega$, the current density and the acoustoelectric field are almost exactly in phase. As ω is increased, the acute angle between the current density and the acoustoelectric field increases which leads to reduction in the acoustic loss. Scattering of the carriers, therefore, plays an important role in acoustic absorption. Thus apart from other effects, the phase mismatch may be one of the factors in limiting the linear gain of an acoustoelectric amplifier. It is well known that the linear gain of this device is limited because of the several nonlinear effects such as high field acoustoelectric domain [6,7], current saturation[8,9], harmonic generation [10] and parametric down conversion of acoustic power to subharmonic frequencies [11,12]. However, it has not been realised that in addition to these effects the different phases of the incoming acoustic wave and the resulting interaction also contribute to the limitation of the linear gain.

4. Absorption coefficient

The absorption coefficient is the ratio of the average power transferred from the acoustic wave to the electrons per unit volume and the incident energy flux. This may, therefore, be expressed as

$$\alpha = \frac{W}{(1/2)\,\rho\,\omega^2\,|\xi|^2\,S} \tag{8}$$

where W is the power transferred from the acoustic wave to the conduction electrons per unit volume and $|\xi|$ is the magnitude of the ionic displacement caused by the acoustic wave.

Since the power transferred between the electrons and the wave is the scalar product of force acting on the electrons and the velocity produced by the wave, we have

$$W = \frac{1}{2} R_e \boldsymbol{F} \cdot \boldsymbol{v}$$

$$= -\frac{1}{2e} R_e \boldsymbol{F} \cdot \boldsymbol{J}_e. \tag{9}$$

Further, since the acoustoelectric current density is

$$\boldsymbol{J}_e = -\frac{\sigma}{e} \boldsymbol{F}, \tag{10}$$

and the self-consistent longitudinal force is

$$\boldsymbol{F} = \frac{\boldsymbol{F}_{\text{ext}}}{1 - 4\pi\sigma/(i\omega)}, \tag{11}$$

we have

$$W = \frac{1}{2e^2} \frac{|\boldsymbol{F}_{\text{ext}}|^2}{1 + 16\pi^2\sigma^2/\omega^2} \cdot \sigma. \tag{12}$$

For piezoelectric crystals such as In Sb, the force is

$$F = e\, q\, \beta\, \xi \tag{13}$$

where q is the wave number and β is the piezoelectric coefficient. Therefore, the absorption coefficient is given by

$$\alpha = \frac{\beta^2}{\rho S^3} \frac{\sigma}{1 + 16\pi^2 \sigma^2/\omega^2}. \tag{14}$$

In order to obtain an expression for σ, we write the current density in the form

$$J_e = \frac{1}{4\pi^2} \iint e\, v_k f_1 \frac{ds}{\hbar |v_k|}\, d\varepsilon, \tag{15}$$

and substitute the real part of f_1 from eq. (6) which yields

$$\sigma = \frac{e^2 k_F^3}{3\pi^2 m^*} \frac{\nu}{\nu^2 + \omega^2}, \tag{16}$$

where k_F is the Fermi wave vector and m^* is the carrier effective mass.

The collision frequency corresponding to the scattering from acoustic phonons has been obtained from [13]

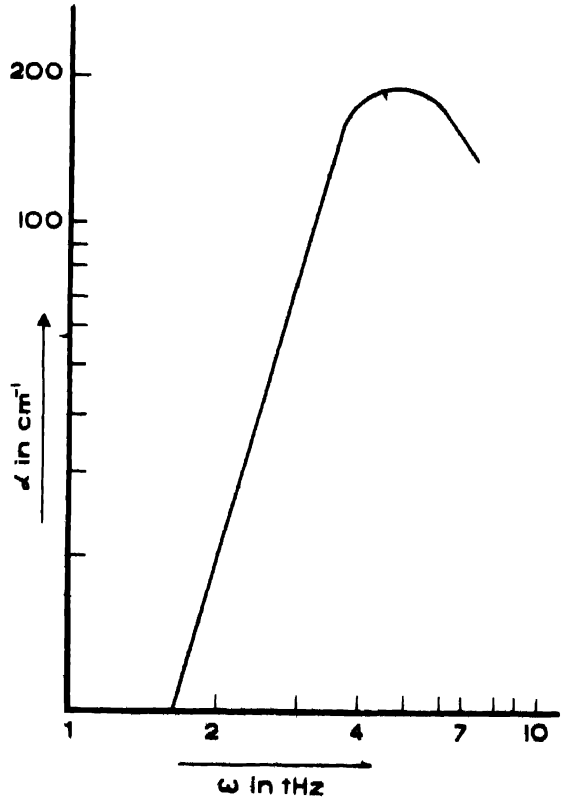

Figure 1. Frequency dependence of the absorption coefficient for n–indium antimonide.

$$v = \frac{\sqrt{2}\, C^2 \left(m^* k_0 T\right)^{3/2}}{\pi\, \hbar^4\, C'} \left(\frac{E_F}{k_0 T}\right)^{1/2} \tag{17}$$

where C is the deformation potential constant and E_F is the Fermi energy.

Absorption coefficient for n-InSb obtained from eq. (14) has been shown in Figure 1. The parameters [14] used in the calculation have been taken to be $n_0 = 3 \times 10^{16}$ cm^{-3}, $\beta = 2.078 \times 10^4$ esu/cm^2, $\rho = 5.8$ gm/cc, $S = 4.0 \times 10^5$ cm/sec, $C = 7.2 \times 10^{-12}$ erg, $C' = 0.672 \times 10^{12}$ dyne cm^{-2} and $T = 300$ K.

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